Thoughts on Power System Flexibility Quantification for the Short-Term Horizon

N. Menemenlis[1], M. Huneault[*], A. Robitaille[‡]

***Abstract*— This paper reviews the notion of flexibility and applies it to the problem of power system adequacy of supply and reserve computations in the face of a class of input uncertainties. It first presents some definitions given to flexibility and flexibility indices in the power systems and process control industries. This is by no means a comprehensive review, but it does highlight some of the main ideas in the field. The notion of flexibility is applied to assess the quality of a solution strategy, based on some initial criterion for a given scenario, for example reliability, and then on its success in satisfying a set of scenarios. The paper then illustrates the use of a flexibility index borrowed from the process control literature to evaluate a solution strategy that provides balancing reserves to mitigate wind generation uncertainties. The paper concludes that flexibility can only be obtained at a cost and that it could prove itself to be a useful tool for the operator in an emerging technological environment.**

***Index Terms*—Operations planning, Balancing reserves, Short-term reliability, Wind-power integration into large systems, Flexibility Index**

I. Introduction

Hydro-Québec (HQ) is in the process of integrating wind power into its power system, with a presently planned capacity of approximately 10% of the total generating capacity by the year 2016. For this reason, HQ has initiated a number of projects to study the system operational and planning requirements to facilitate and eventually optimize the integration of wind energy into its system. The studies have already provided useful results but still leave the fundamental question of the quantification of the overall impacts that intermittent energy sources would have on the system. On one hand, the technical impacts include a change in planning and operations strategy resulting in different power and energy margins associated with the different scenarios. On the other hand, these system modifications come at a cost, defined in terms of actual or opportunity costs.

[1]* IREQ, Varennes, QC, Canada, nickie@ireq.ca
‡ Hydro-Québec Production, Dir. Planification de la production éolienne, Direction générale, Montréal, QC, Canada.

Work supported by the office of strategic development projects of the Hydro-Québec Research Institute.

Incorporating uncertainties in power system studies, such as those of wind generation, is not a new problem. In the past, uncertainties associated with demand and generator unavailability have been incorporated in planning and operations problems. With the advent of power system technology innovations such as wind and other emerging forms of intermittent generation and load technologies however, the consequences of uncertainties become more accentuated.

Traditionally, operators have striven to satisfy their demand, assuring both high levels of reliability and a low cost in a manner that is equitable to all their users. They are aided by tools such as unit commitments over time, using as input the load forecasts, available generation capacity, upcoming market transactions and required reserve levels. Often the latter are predetermined using known criteria and are padded to assure acceptable reliability levels. When the uncertainties addressed by the reserves have a certain temporal cyclicity, such as that on the seasonal load, this is reflected in the reserves levels that allow the system to maintain a certain performance. However, when the phenomena acting upon a system are completely random, it is recognised that the system needs additional reserves to satisfy the "same" performance criteria as before their appearance. The additional reserve requirements can vary widely based on the perceived upcoming input uncertainties' statistical characteristics.

To maintain their existing quality in balancing supply and demand, it becomes necessary for utilities to manage the greater degree of uncertainty that recent innovations have introduced. This is true within every time-horizon, for problems ranging from long-term power system and energy resource planning to short-term operations.

Different avenues can be considered to solve the wider problems involving uncertainties in input variables. Some problem formulations have encapsulated these uncertainties in a single complex problem formulation amenable to a solution. Examples are linear multistage stochastic programming for resource planning, like Stochastic Dual Dynamic Programming (SDDP) [1], and stochastic unit commitment [2]. Their complexities do impose limits on the size and comprehensiveness of their solutions. A shortcoming of the solution algorithms for these methods is that the choice of a finite number of representative realisations becomes critical to the convergence of the method to the proper

978-1-4577-1002-5/11/$26.00 ©2011 IEEE

solution [3]. For many problems involving uncertainties, the stochastic programming approach is most likely unrealistic, as they present a continuum of input scenarios which cannot all be foreseen or quantified. Further, the presence of a large number of random variables plagues the resolution of these problems. Hence frequently no single compact mathematical methodology is available to attack the complete problem.

Two other approaches can be followed to solve planning and operations problems involving uncertainties. A first approach consists of repeating the solution process for a number of plausible realization-scenarios, to each of which is attached some measure of probability. A realization-scenario is a snapshot of an anticipated sequence of events in the future. These can be generated in a number of ways (probability trees, Monte Carlo simulation, etc.) and their number could be quite large. A solution strategy would then be chosen to accommodate at least a given proportion of the realization-scenarios. The second approach consists of capturing the uncertainty of the input variables using probabilistic tools within the solution process. However, even using probabilistic tools, problems are often formulated to address only one probabilistic scenario of inputs. This was the case in our previous work which computed balancing reserves to mitigate the effects of wind generation forecast uncertainties based on reliability criteria [4]-[5].

We argue in this paper that traditional system planning or operating practices based on a limited number of input scenarios and a single criterion may not be adequate. This is because a solution ensuring, say, a given level of reliability or security for one input scenario may not be adequate for a continuum of input scenarios. One thus needs a further methodology to select among the candidate solutions. We refer to the outcome of this methodology as the "solution-strategy".

Clearly, not all scenarios need be satisfied as some may occur rarely or might be inconsequential. Rather than accommodating all scenarios with a solution-strategy and its attributed resources, the solution-strategy can be shaped to satisfy a supplementary (scenario-related) criterion. The latter could be based on satisfying a certain level of success of the solution-strategy over the set of scenarios, either in terms of occurrences through their enumeration or their probability of occurrence [6], or in terms of limiting incurred costs [7] beyond those of a base case. Alternatively, a given solution-strategy could be evaluated in terms of the proportion of the scenarios it satisfies. This is where the notion of flexibility comes in.

Flexibility has become an important topic of late in power system studies, with the recognition that uncertainties will become more important in future. Occurrences of success, limiting costs, or a combination of both have formed a basis for a measure of flexibility. The introduction in [8] defines two notions of flexibility in simple, all-encompassing statements. First, it refers to Stigler [9] who defines economic flexibility as "the ability to adapt to a wide range of possible demand conditions in the short run at little additional cost". Second, it adapts the definition of flexibility for power systems by defining a flexible plan as "one that enables the utility to quickly and inexpensively change the system's configuration or operation in response to varying market and regulatory conditions." It notes that the definition of flexibility resembles those of related complementary concepts of adaptability (change to accommodate new conditions) and robustness (satisfying all conditions in advance).

We note here that flexibility is a notion that must be related to and can only be defined within specific problem formulations, and by extension specific areas of study. Hence a single, general-purpose measure of flexibility does not make sense.

The remainder of the paper is organised as follows. In Section II. we review the notion of flexibility as presented in different areas of power system studies. In Section III. we summarize the computation of a flexibility index as presented in the literature in the area of processes control and we borrow it to define one for a particular problem in power systems operations. Section IV. presents arguments for a flexibility index. In Section V. we present the particular problem to which we want to apply a flexibility index. Section VI. develops the methodology to compute a flexibility index for the balancing reserves problem. Section VII. presents the effect of constraints on the flexibility index which could represent cost limitations on the solution.

II. FLEXIBILITY IN DIFFERENT AREAS OF POWER SYSTEM STUDIES

The literature presents the notion of flexibility with many connotations applied to many different applications. Several examples are cited in the following.

The *transmission expansion planning problem* consists of meeting future load through judicious additions to the network, despite uncertainties in load growth [10] or generation expansion [11]. Both of these references propose measures of flexibility based on reliability criteria. In [10], an optimal expansion plan is one which covers the load growth scenarios at minimum cost, with one cost component attributed to the unserved demand. The proposed flexibility index is precisely the expected unserved demand. This index covers a large range and is favourable when its value is low. In [11], network expansion is evaluated in response to various generation scenarios in a free market environment. The proposed flexibility index is an average of the load flow distribution factors of the branches, weighted with the current margins of the corresponding branches. A network is considered flexible if the index is small, as a result of network flows exhibiting low sensitivities with respect to variations in generation.

The *generation expansion planning problem* in [12] and [13] consists of choosing a generation mix which minimizes exposure to economic risk. In [12], in a pre-deregulation environment, the generation expansion satisfied the

deterministic load growth over a time horizon, considering generation mix scenarios over the fixed or variable costs of the different generation technologies. The proposed flexibility index provides the sum of additional cost incurred by the scenarios with respect to an optimal base case. Again, the solution deemed most flexible is the one with the lowest sensitivity with respect to variations within the scenarios. In the more recent [13], the generating entities are participants in energy markets. Their expansion strategy is complex, involving a three-pronged composite index. One component is a flexibility index computed as the standard deviation of the additional costs incurred by the scenarios.

Another problem of interest is that of *assessing current transmission adequacy* with respect to uncertain generation expansion. A flexibility index could indicate if the transmission system holds enough margins to accommodate a range of generation expansion scenarios. These could appear with little pre-planning in a deregulated environment. In [14], two flexibility indices are proposed, one in terms of network flow margins alone, the other also including economic terms. Note that this approach could also be applied on an operations time horizon to assess the flexibility of a network with widely varying power dispatch or market-clearing patterns.

We note two topics in the *power systems operation* literature where the notion of flexibility is applied. In the first topic [15] [16], the general argument stresses the necessity to maintain *flexible system resources* able to respond to variable generation. Identified resources are fast responding generation (gas, hydro technologies) for energy, ramping and reserves, responsive load management options, storage, fast markets to clear the sale of variable generation and the adjustment of other generation resources to maintain load-generation balance, and interconnections through which resources can be shared. Reference [16] does not propose a flexibility index as such, but rather suggests reliability criteria to assess the flexibility of a system. To accommodate variable generation, it introduces an added reliability measure for ramping capability, similar to LOLP for energy sufficiency. The second topic concerns the addition of *flexibility constraints in operations computational tools* eg. imposing balancing reserves related to wind generation variability as a flexibility constraint in a unit commitment to mitigate the effects of the latter [17].

III. Definitions of Flexibility in Process Control

A large body of literature on flexibility exists in the process control field. There flexibility alludes to the designs of control processes which with minimum alteration and changing costs can adapt to the production of new products. This can reap large performance gains [7].

In our power systems application which follows, we borrow a methodology from [6]. A graphical illustration of the evolution of the flexibility index is shown in Figure 1. Consider for illustrative purposes three physical variables with respect to which we want to define a flexibility index, say energy, ramp rates and economic considerations for a given time horizon. The values of the variables in the candidate solutions satisfy a reliability criterion.

- The candidate solutions corresponding to all retained input scenarios are introduced into a multidimensional space to form an operating region (uncut polyhedron), not necessarily entirely within the available system capacity.
- The constraints on the physical variables without regard to reliability form the outer limits on a constraint specification region (cube), corresponding to available resources committed by a unit commitment.
- The intersection of the operating and constraint specification regions forms the feasible region (cut polyhedron) and corresponds to potential needs that should be met by the provided resources.

The ratio between measures of the feasible region and the operating region is defined as a flexibility index.

$$Flexibility\ index = \frac{\text{Volume of cut polyhedron}}{\text{Volume of uncut polyhedron}} \tag{1}$$

This index necessarily takes on values between 0 and 1, and indicates maximum flexibility at a value of 1. The aforementioned regions can vary over time, resulting in a dynamic index evaluated over time.

This approach is feasible as long as the dimensionality of the problem is chosen to be low.

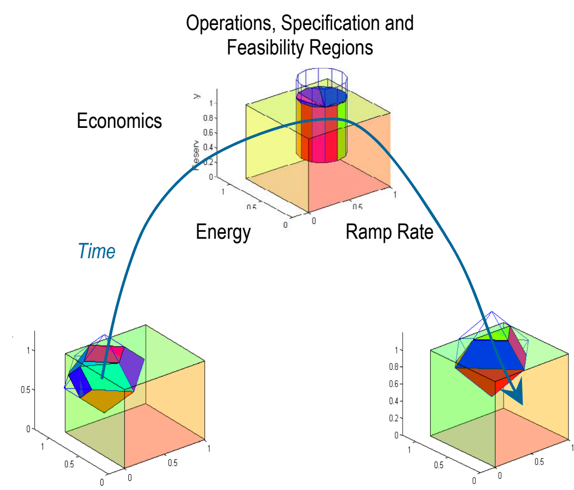

Figure 1. Illustration of the temporal evolution of the operating region (polyhedron), constraint specification region (cube) and their intersection forming the feasible region.

IV. WHY A FLEXIBILITY INDEX FOR THE POWER SYSTEM OPERATIONS PROBLEM

Suppose that a new intermittent generation technology has been implemented in a power system. Further, suppose that the operating strategy is based on a single input scenario, for example the most probable generation.

Certain questions arise. How "well" was the system operating before and how well will it operate after the incorporation of the new intermittent technologies? Given a certain criterion of wellness, this question has been answered for a single input scenario in our previous work for the case of balancing reserves. In fact the system solution-strategy can be adjusted to maintain the given level of wellness [5].

In the presence of multiple input scenarios could this level of wellness be maintained? What are the incremental impacts to operators and what is a good measure of quality of an operating strategy after the incorporation of these new technologies? Should the performance criteria, for example reliability, remain at the same level? Should cost be added to the performance criteria? Should technical performance criteria be maintained at any cost? If not, at what cost? How do we re-compute new levels of performance and how do we evaluate whether the system is better off? A flexibility index as defined below could help answer many of these questions.

How could this index be made useful to the system operators? What input information would they require to compute it and then use it? For the application studied in this paper, in keeping with [6] but applying the notion to a probability space, we propose a measure of flexibility as the proportion of input scenarios being satisfied by an operating strategy, whether it be predefined or adaptable.

In the next section we define this flexibility index and test its computability and usefulness for the particular problem of adequacy of supply which results in determining balancing reserves on the hours-ahead time horizon.

V. COMPUTATION OF BALANCING RESERVES WITH THE INCORPORATION OF INTERMITTENT GENERATION

The problem for which we will create a flexibility index is as follows. In the operations time-horizon of 1-48 hours ahead, balancing reserves are required to mitigate the effects of load and generation forecast uncertainties. The magnitude of these balancing reserves is chosen to maintain a certain level of reliability. Now, when integrating wind generation in a power system, operators strive to maintain the same level of reliability (quality of service or wellness) as before its incorporation.

This is achieved by applying an additional quantity of balancing reserves. Its computation requires as input wind power generation forecasts, wind generation and load error forecast statistics and generation outage data. An example of the reliability index, denoted Risk, before and after the incorporation of wind generation and the corresponding addition in balancing reserves, denoted ΔBR, is shown in Figure 2. The details of the computation are given in [1] and [5]. Balancing reserves including the additional ones are committed in the day-ahead and same-day operations plans.

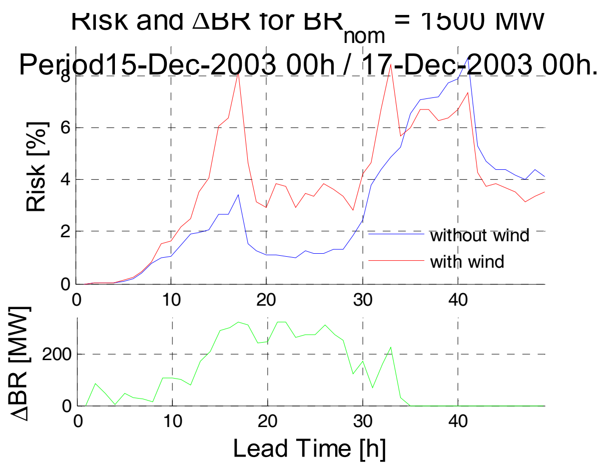

Figure 2. Evolution of risk with and without wind generation as a function of lead time and additional balancing reserves required to maintain the same level of risk with wind generation as without wind generation.

VI. CREATION OF SCENARIOS AND THE COMPUTATION OF A TECHNICAL FLEXIBILITY INDEX

The result for a single input load/generation probabilistic scenario of the previous section can be considered as a base case for a multi-scenario case.

Since the inputs required for the above computation are forecasts based on a very complex physical phenomenon, namely weather, it is conceivable that several somewhat different weather forecasts could be valid each possibly associated with a given probability of occurrence, depending on the prevailing meteorological regime.

In fact, several weather forecast methodologies are run concurrently. Each methodology is advantageous for some meteorological conditions and topographies, but not for all. These forecasts may differ both in magnitude and temporal characteristics. This is particularly true in wind forecasting. In particular, the wind generation forecasts seriously digress when unforeseen delays of passing wind fronts occur. This degrades the previously computed power balance strategy which had committed conventional generation. Both load and wind generation forecasts are sensitive to weather forecasts. Though so far we have not considered the influence of other types of variables on our input data, the approach is general and could be extended.

At this point we proceed to capture the multiple input scenarios using a probability tree with three variables as

illustrated in Figure 3. For example, the three input variables could be load, wind generation and energy market prices. Here two scenarios are considered for the first variable x^1_{Sc1} and x^1_{Sc2} which occur with probabilities p^1_1 and p^1_2 respectively. Three scenarios are further considered for the second variable, x^2, and two for the third variable, x^3. This tree ends in 12 leaves, each leaf representing a scenario. The values of their variables are taken on the nodes leading to each leaf and their probabilities are taken as the product of the probabilities on the branches leading the leaf. For example the top leaf is realised with the first scenarios of each of the three variables, i.e. $\left\{x^1_{Sc1}, x^2_{Sc1}, x^3_{Sc1}\right\}$, and its probability is equal to $p^1_1 \times p^2_1 \times p^3_1$.

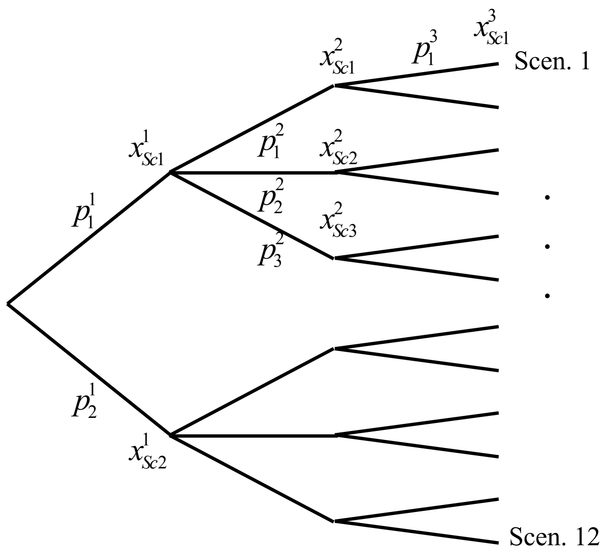

Figure 3. Illustration of a probability tree to build probabilistic scenarios.

Once all the scenarios are formed, the rare events could be filtered out.

Reconsider the computation of balancing reserves of Section V. for a number of input probabilistic scenarios, all available simultaneously and each with a given probability of occurrence. To each scenario is associated a solution for balancing reserves, for each of which we must maintain a given reliability level. However, only one solution can be retained since it has to be committed in advance. Clearly, a solution for any one scenario would not necessarily satisfy the reliability requirements of other scenarios. The question is which balancing reserves should be used to best satisfy most of the scenarios: a solution corresponding to one scenario, a combination of scenarios or an entirely new solution based on other considerations. Then the quality of the chosen solution can be verified as to how well the remaining scenarios are satisfied. A table or a graph illustrating all the candidate solutions together might facilitate the choice of a winning solution strategy.

In the following example, the base case is realistic whereas the created scenarios are artificial but realistic and predetermined. Nonetheless there is no loss of generality for the principles we want to illustrate.

Figure 4 illustrates computed balancing reserves solutions to maintain a given reliability level as a function of lead time for a limited set of input scenarios. Each solution inherits its probability of occurrence from its input scenario. At any given time, the balancing reserves for one scenario also satisfy the required reliability levels on all scenarios below it. A solution that would satisfy reliability requirements for all scenarios would form an envelope over the trajectories. Clearly, the solution trajectories interweave over time, as a direct consequence of the very different temporal characteristics of the forecast uncertainties between scenarios. Since no single solution trajectory achieves the highest position at all times, we cannot adopt a solution strategy corresponding to one scenario. In the example illustrated in Figure 4 three possible but arbitrary solution strategies are considered: Strat. 1 corresponds to the most probable input scenario shown in the black line, Strat. 2 corresponds to Strat. 1 augmented by 10% (blue) and Strat. 3 corresponds to the weighted average of the solutions (purple).

Next, we define the flexibility index as the sum of the probabilities of the scenarios satisfied by the chosen solution strategy. This is illustrated in Figure 5. Looking at any of the three strategies, the flexibility index is relatively high when most candidate solutions appear below that strategy. Conversely, a low flexibility index indicates that most candidate solutions appear above that strategy.

The flexibility index of Strat. 1 oscillates between high and low values. The slight augmentation of balancing reserves attributed to Strat. 2 improved the flexibility index by reducing the downturn in the oscillations and lifting the curve in general. For Strat. 3 the balancing reserves being always in a median position, its flexibility index is of the order of 0.5.

We note that small differences in values of balancing reserves in the three strategies can translate into large differences in the flexibility index. This is because they are related to the order of their positions and the distance between the curves. The relationship between the retained strategies and their flexibility indices is very complex and depends on the underlying phenomenon.

The graphical representation has illustrated how a strategy can be chosen to achieve an acceptable flexibility index.

A further example could be to choose a strategy to maintain a certain flexibility level over every time step. This could be achieved by placing a new solution strategy curve such that the sum of the probabilities of the curves below it is at least equal to the desired flexibility level.

If changes occurring during the operational time horizon can be captured in new scenarios, as they become available, then the methodology is general enough to capture them. The resulting strategy will be said to be adaptable.

Alternatively, this flexibility index could be computed sequentially for different time horizons, or in a sliding window, so as to give an idea of the evolution of flexibility of the system to the system operator, much like the "flying brick" concept in [17]. This is referred to as flexibility with respect to manoeuvrability.

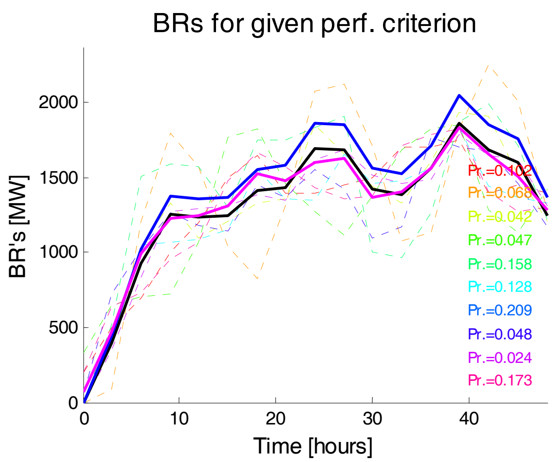

Figure 4 Required balancing reserves for different scenarios accompanied with their probability of occurrence and three retained solution strategies.

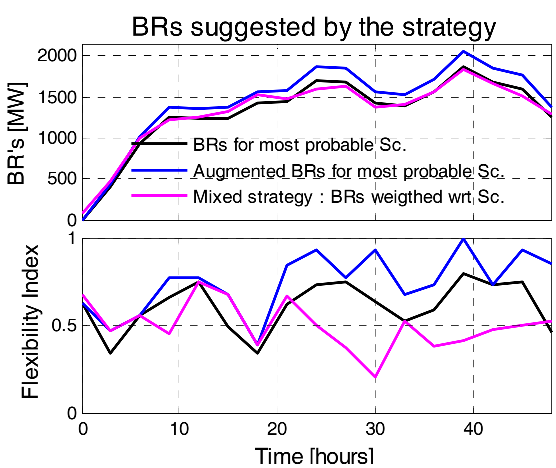

Figure 5 Three balancing reserve strategies and their corresponding flexibility indices over time.

The example presented here considers only one dimension but can easily be extended to several dimensions. For the three-dimensional problem alluded to in Figure 1 at a given instant several candidate solutions are plotted as points. The blue points within the ellipse represent scenarios satisfied by the solution strategy. Two solution strategies are represented in Figure 6 corresponding to probabilities of success of 90% and 60% respectively.

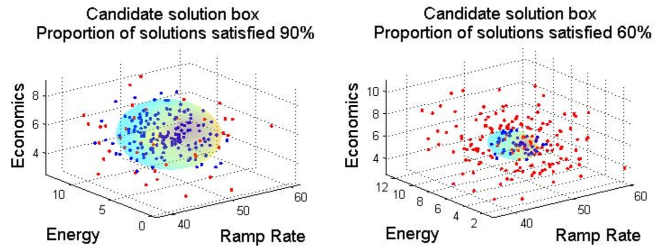

Figure 6 Flexibility index seen as the ratio of the candidate solutions satisfied by the solution strategy in three dimensions.

Up to this point we have built a flexibility index based on technical issues. Such a flexibility index by itself is insufficient for two reasons. First, because the required level of flexibility is specific to the application and the perceived needs of the operator. Further, the cost of the strategy has not yet been included. Small differences in values of balancing reserves in the three strategies can translate into large differences in the cost of implementation.

VII. Augmenting the Technical Flexibility Index with Economic Issues

The cost considerations present themselves as a constraint on the solution strategies. Given such a constraint the solution strategy is modified and its effect appears on the flexibility index. Hence there is a cost associated with flexibility.

This is illustrated in the following Figure 7 which recreates Figure 5. It shows the effect of adding a constraint on the maximum value of balancing reserves which could be equivalent to a cost constraint. We note that with such an added constraint the flexibility index is compromised.

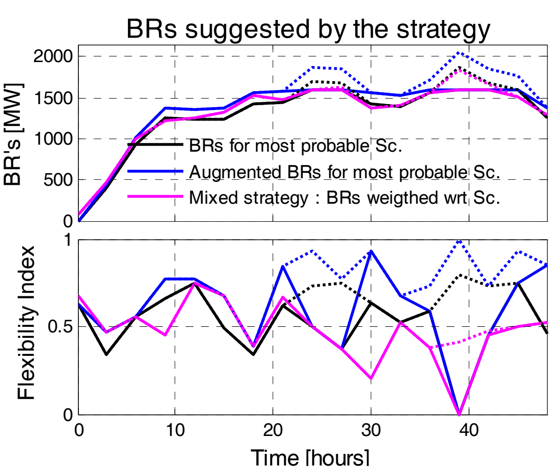

Figure 7 Three balancing reserve strategies and their corresponding flexibility indices over time. The dotted lines represent the unconstrained solution strategies and corresponding flexibility indices.

VIII. Summary and Conclusions

In this paper we presented some thoughts on the computation of a technical flexibility index for a particular application in power systems. The idea was borrowed from the process control area and was applied to the problem in operations planning. Several graphical clarifying examples were given. We pointed out that a flexibility index should be related to specific problem formulation and criteria of design. Finally, we argued that flexibility can only be obtained at a cost. Lastly, we show that a feasibility index computation could be rather easily incorporated in the computation of operations planning. Figure 8 below reproduces the many elements of the computation presented earlier in an operations planning environment in a single coherent plan. This could prove itself to be a useful tool for the operator.

References

[1] M.V.F. Pereira and L.M.V.G. Pinto, Multi-stage stochastic optimization applied to energy planning, Mathematical Programming, 52, 359-375, 1991.

[2] Aidan Tuohy, Peter Meibom, Eleanor Denny, Mark O'Malley, "Unit Commitment for Systems With Significant Wind Penetration, IEEE Transactions On Power Systems, Vol. 24, No. 2, May 2009, pp. 592-601.

[3] A. Shapiro, Analysis of Stochastic Dual Dynamic Programming Method, 2009, http://www.optimization-online.org/DB_FILE/2009/12/2509.pdf .

[4] N. Menemenlis, M. Huneault, J. Bourret, A. Robitaille, "Calculation of Balancing Reserves Incorporating Wind Power into the Hydro-Québec System over the Time Horizon of 1 to 48 Hours", 8th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks of Offshore Wind Farms, 14-15 October, 2009, Bremen, Germany.

[5] N. Menemenlis, M. Huneault, A. Robitaille, "Computation of Dynamic Operating Balancing Reserve for Wind Power Integration for the Time-Horizon 1-48 Hours", 9th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks of Offshore Wind Farms, 18-19 October, 2010, Quebec City, Quebec, Canada.

[6] David Kazmer, David Hatch, Liang Zhu, Christoph Roser, Deepak Kapoor , "Definition and Application of a Process Flexibility Index", Transactions on ASME, Vol. 125, February 2003.

[7] Mable Chou, Chung-Piaw Teo, Huan Zheng , Process Flexibility: Design, Evaluation and Applications, August 2008, http://www.bschool.nus.edu.sg/Staff/bizteocp/ flexireview.pdf .

[8] Benjamin F. Hobbs, Jeffrey C. Honious, Joel Bluestein, "Estimating the Flexibility of Utility Resource Plans: An Application to Natural Gas Cofiring for SO_2 Control", IEEE Transactions on Power Systems, Vol. 9, No. 1, February 1994, pp 167-173.

[9] G. Stigler, "Production and Distribution in the Short Run," J. Political Econ., Vol. 47(3), pp. 305-327, 1939.

[10] M. Lu, Z.Y. Dong, and T.K. Saha, "Transmission Expansion Planning Flexibility", IPEC 2005, The 7th International Power Engineering Conference, 29 Nov.-2 Dec. 2005, Singapore.

[11] P. Bresesti, A. Capasso, M.C. Falvo, S. Lauria, "Power system planning under uncertainty conditions. Criteria for transmission network flexibility evaluation", paper presented at 2003 IEEE Bologna Power Tech Conference, June 23th-26th 2003, Bologna, Italy.

[12] R. Tanabe K. Yasuda R. Yokoyama, H. Sasaki, "Flexible Generation Mix Under Multi Objectives and Uncertainties" IEEE Transactions on Power Systems, Vol. 8, No. 2, May 1993, pp. 58 1-587.

[13] Ali Zangeneh, Shahram Jadid, Ashkan Rahimi-Kian, "Uncertainty based distributed generation expansion planning in electricity markets", Electr Eng (2010) 91:369–382.

[14] A. Capasso, M.C. Falvo, R. Lamedica, S. Lauria, S. Scalcino, "A New Methodology for Power Systems Flexibility Evaluation", Proceedings of IEEE Power Tech Russia 2005, Saint Petersburg, Russia, June 27-30 2005.

[15] Wind Energy The Facts, Part II Grid Integration, pp 170-172, http://www.wind-energy-the-facts.org/documents/download/Chapter2.pdf .

[16] Eamonn Lannoye, Michael Milligan, John Adams, Aidan Tuohy, Hugo Chandler, Damian Flynn, Mark O'Malley, "Integration of Variable Generation: Capacity Value and Evaluation of Flexibility", 2010 IEEE Power and Energy Society General Meeting, Minneapolis, MN, July 25-29, 2010.

[17] Shuai Lu, Yuri V. Makarov, Yunhua Zhu, Ning Lu , Nirupama Prakash Kumar, Bhujanga B. Chakrabarti, "Unit Commitment Considering Generation Flexibility and Environmental Constraints", paper presented at IEEE PES General Meeting, 25-29 July 2010, Minneapolis.

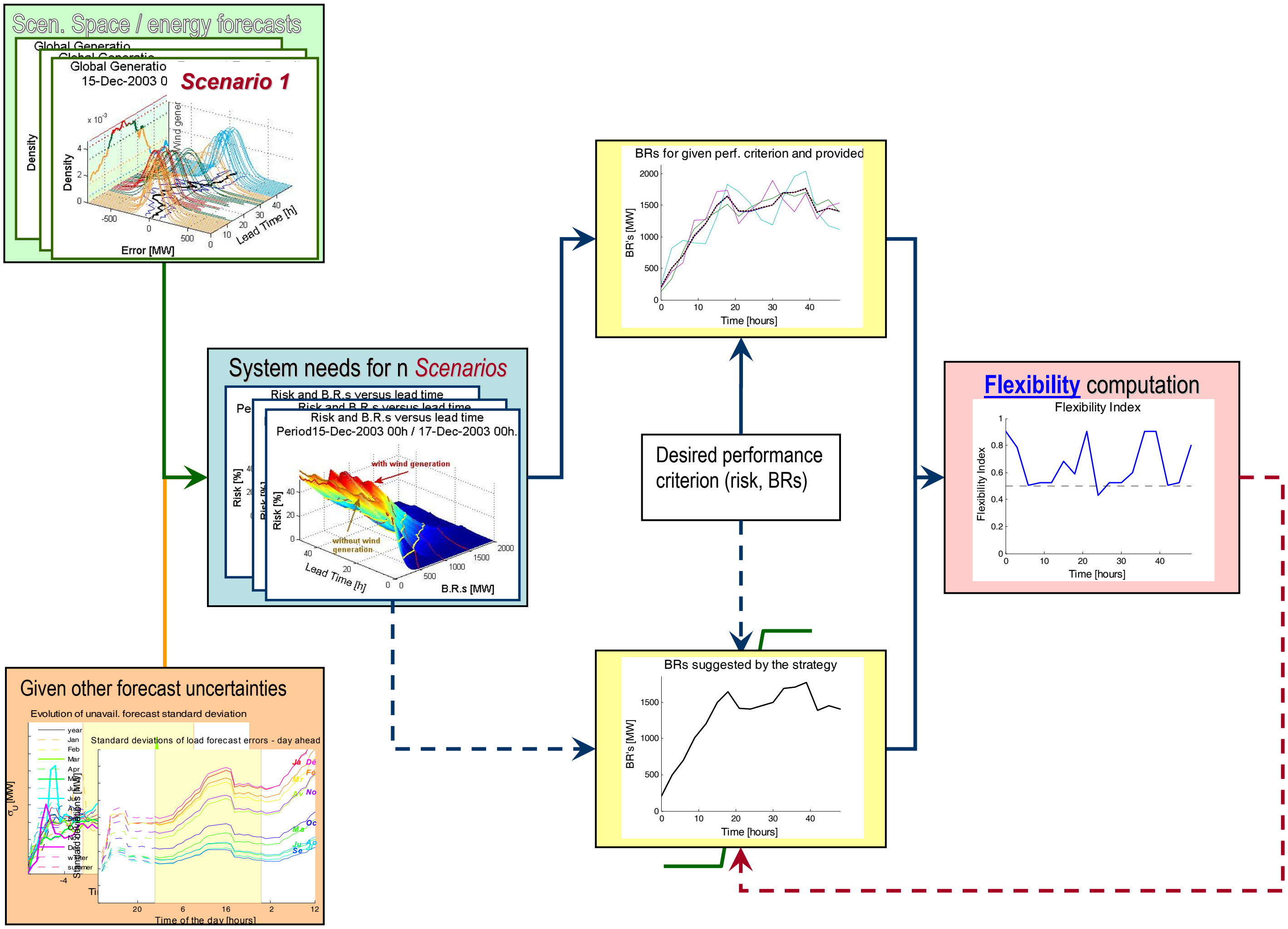

Figure 8. General diagram of flexibility index computation.